昆 虫 学 报 *Acta Entomologica Sinica*, December 2016, 59(12): 1376 – 1385　　doi:10.16380/j.kcxb.2016.12.011

Optical remote detection of flying agricultural pest insects using dark-field reflectance measurements

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Abstract: 【Aim】 The aim of the present study is to develop an optical remote sensing technology to automatically monitor insect pests in agricultural fields day and night. 【Methods】 A small reflective telescope was arranged facing a distant dark box, providing a low-light-level base line. When insects flied into the telescope field of view, they scattered light from the sun, and the optical information could be collected by the recording system attached to the telescope. At night we instead employed a strong lamp for insect illumination. 【Results】 Insect counting, wing-beat frequency analysis and reflectance spectra recordings were all successfully achieved. This illustrates the possibility to monitor agricultural insect pests with a dark-field back-scattering detection system. Each released known insect species showed a unique reflectance spectrum character. Several insect species, in particular *Conogethes punctiferalis* (Guenée) and *Xenocatantops brachycerus* (Willemse) were successfully distinguished from each other by employing the method we introduced. 【Conclusion】 The dark-field back-scattering detection system is practical for monitoring agricultural insect pests in the field through day and night. The wing-beat frequency as well as the spectral contents could be used for pest insect recognition as anticipated.

Key words: Optical remote sensing; dark-field back-scattering detection; insect; *Conogethes punctiferalis*; *Xenocatantops brachycerus*

1 INTRODUCTION

Insects, with vast species abundance and wide geographic distribution, constitute a major part of the atmospheric fauna and play an important role in the ecosystem of our biosphere. Most insects, like other organisms, feed on vegetation. With the development of agriculture, more and more land has been cultivated for crops, and forest-, meadow- and wetland-areas are diminishing, which pushes insects to adapt to agricultural crops. The insect/agricultural interrelations thus become increasingly important, not the least from an economical point of view. Some insect species migrate over long distances at high altitudes, and remote sensing techniques are thus of great interest to complement conventional research approaches (Chapman *et al.*, 2011).

Remote monitoring of insects mostly is a matter of radar technique application, and much information can be gained in radar studies (Chapman *et al.*, 2003, 2011). Acoustics also provide active remote sensing possibilities at shorter ranges (Raman *et al.*, 2007) as amply demonstrated by the sophisticated bat insect localization system (Schnitzler and Kalko, 2001). In contrast, optical techniques can add the spectral dimension to the characterization and identification of insects. As in radar, optical wing-beat frequency monitoring also provides identification means.

Recently, laser-based techniques were introduced to monitor specially trained honey bees, aiming at indirect remote detection of hidden land mines (Shaw *et al.*, 2005; Carlsten *et al.*, 2011). These techniques were extended to more general purpose studies of different insect species by

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基金项目：广东省创新科研团队项目(201001D0104799318)；国家自然科学基金项目(31401731)

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收稿日期 Received：2016-09-02；接受日期 Accepted：2016-11-24

researchers of Lund University, and fluorescence spectra and wing-beat frequencies were monitored (Brydegaard *et al*., 2009; Guan *et al*., 2010; Mei *et al*., 2012; Brydegaard *et al*., 2014). Runemark *et al*. introduced a particularly simple and convenient optical remote sensing technique employing dark-field monitoring (Runemark *et al*., 2012). In this approach a small reflective telescope is set up in an insect habitat, and pointing to a remote termination, which is arranged to be as dark as possible. Thus, a very low signal is photo-electrically recorded, on top of which strong intensity spikes are observed when sun-lit insects fly into the narrow field-of-view (FOV) of the telescope. By fast read out, wing-beats can be discerned, exhibiting fundamental as well as characteristic overtone spectra (Brydegaard *et al*., 2014). Further, the total reflectance spectra can be read out at high capturing rates, allowing the spectral contents of the abrupt insect spikes to be analyzed for species and gender identification (Runemark *et al*., 2012). This offered a promise for better remote identification of species and even gender than radar did.

In the present study in Henan province, a main agricultural area in China, daytime observation using sun/sky radiation was extended to night-time monitoring of agricultural pest insects using an artificial light broad-band illuminator.

2 MATERIALS AND METHODS

2.1 Location and insects

We performed a field trial in Zhengzhou, Henan province, which lasted for 3 weeks in August/September of 2015. Henan province is located in the Huang-Huai Plain (flood plain of the Yellow River and the Huaihe River) where favorable climate and soil conditions make it an ideal region for crop production, specifically for wheat and corn. This area is regarded as the cradle of the Chinese nationality. The agricultural cultivation originated several thousand years ago feeding a large population and led to a unique culture and civilization. Damage caused by insect pests is one of the major concerns for crop protection. Two experimental sites were selected in the vicinity of the Yellow River. One site (113.599° E, 34.863° N), the Maozhuang experimental farm of Henan Agricultural University (HAU), is located on the south bank of the river, while the other one (113.696°E, 35.005°N), the 2nd Experimental Base of Henan Academy of Agricultural Sciences (HAAS), is located on the north bank of the river.

Insects, based on behavior, can be divided into diurnal and nocturnal groups. Typical diurnal insects are flies, dragonflies, butterflies and grasshoppers. Grasshoppers *Xenocatantops brachycerus* (Willemse) and *Acrida cinerea* (Thunberg) (Fig. 1) were common diurnal species that were easy to catch in the field and were used as the main released targets in day-time. Nocturnal insects are mainly moths. In the 2nd Experimental Base of HAAS, a vertical looking light-trap was employed to catch nocturnal insects. This type of light trap consisted of a 1 kW metal halide lamp at the focus of a parabolic mirror suspended upward at the center of a large metal funnel with a net beneath it, produced a light "pillar" pointing vertically up into the sky. Nocturnal species are sensitive to the blue light (around 430 nm in wavelength) of the lamp, and are attracted and trapped from high altitude. This type of light-trap was earlier used to provide supplementary nocturnal species identification of radar targets (Feng *et al*., 2003) and caught enough nocturnal insects for our controlled release experiment.

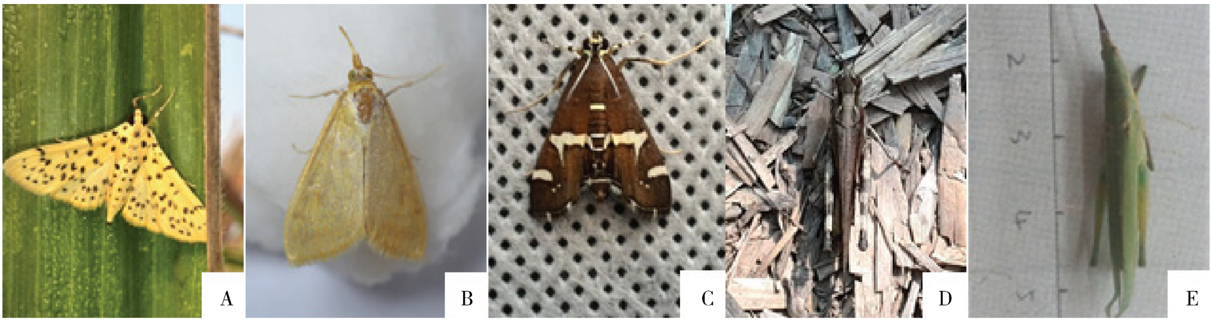

Fig. 1 Selected agricultural pest insect species in Henan province

A: Yellow peach moth, *Conogethes punctiferalis* (Guenée); B: Asian corn borer, *Ostrinia furnacalis* (Guenée); C: Hawaiian beet webworm *Hymenia recurvalis* (Fabricius) and grasshoppers; D: *Xenocatantops brachycerus* (Willemse); E: *Acrida cinerea* (Thunberg).

The Asian corn borer *Ostrinia furnacalis* (Guenée), yellow peach moth *Conogethes punctiferalis* (Guenée) and Hawaiian beet webworm *Hymenia recurvalis* (Fabricius) were common crambid species (Lepidoptera: Crambidae) caught in the light-trap (Fig. 1). These three species have similar size and

O. furnacalis and *C. punctiferalis* are major pests of corn in the Huang-Huai Plain. The Asian corn borer *O. furnacalis* is a close relative of the European corn borer *O. nubilalis* and one of the worst corn pests in the western Pacific region of Asia. The larva feeds on almost any part of the corn, damaging the fruit when it bores into the ear to feed on the silk and kernels, and causes devastating losses in a corn field (https://en.wikipedia.org/wiki/Ostrinia_furnacalis). The yellow peach moth *C. punctiferalis* is a widely distributed pest species feeding on peach, sorghum, corn and sunflower in China. The number of generations of this species varies from 1 – 2 generations a year in the northeast region to as much as 5 generations a year in the south region of its habitat. In Henan province, there are 4 generations each year, and the fourth generation overwinters in the form of larva. The Hawaiian beet webworm *H. recurvalis* is a worldwide distributed pest and its larvae feed on beets, chard, spinach, and various weeds such as *Amaranthus* and *Chenopodium* species (http://bugguide.net/node/view/9731; http://www.cabi.org/isc/datasheet/28245). We focused on *C. punctiferalis*, not only because of its pronounced color of the adults suitable for spectral detection, but also because of its massive abundance in the season of the experiments.

2.2 Dark-field back-scattering detection system

The principle of dark-field back-scattering detection is that an illuminated object, such as a flying agricultural pest insect, has a higher optical contrast against a low luminosity background, *e. g.*, black background. Experimental arrangements are shown in Fig. 2(A). A low-cost 8 inch diameter Cassegrainian telescope (Celestron) with a focal length of 2 m was used to collect scattered light. The telescope was placed on a motorized stage allowing horizontal and vertical adjustments using steerable electric motors. It was adjusted to point into a black termination through a 100 m long track in an agricultural field (Fig. 2: B). The black termination was a carefully prepared black box of size 1.8 m × 1.8 m × 2.0 m with one side open and the walls shadowing the FOV termination (Fig. 2: C).

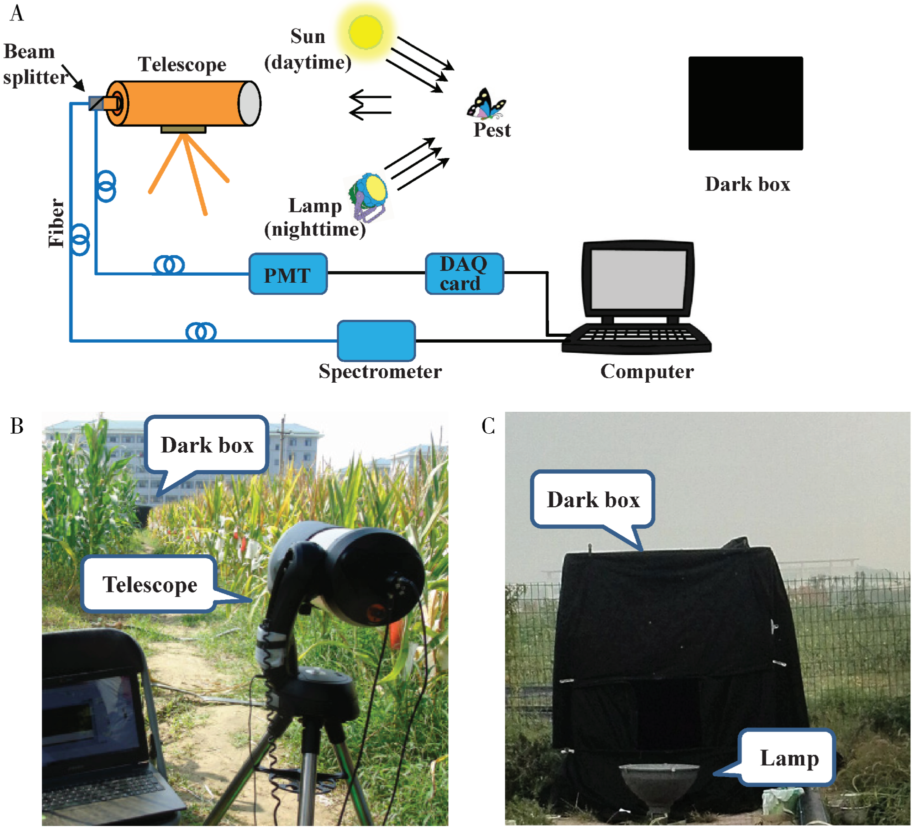

Fig. 2 Experimental arrangements for dark-field remote insect recordings

A: Schematic diagram of the field set up of the dark-field optical spectroscopy system; B: Photo of a set up in corn fields at the Maozhuang experimental farm of Henan Agricultural University, with rice, tobacco and grapes cultivated nearby; C: Photo of a dark termination and a metal halide lamp at the 2nd Experimental Base of Henan Academy of Agricultural Sciences. The telescope arrangement was here placed under an existing construction, providing shelter against strong solar radiation or occasional rain showers.

A 50% beam splitter was attached directly to the telescope, replacing the eye piece. Half the optical flux was fed to a compact photo multiplier tube (PMT; Hamamatsu Model: H11526-11-NF, with an 8 mm diameter detector area) to achieve high sensitivity and signal-to-noise ratio (SNR). Alternatively, we used a silicon-photodiode non-spectroscopic intensity detector (Hamamatsu, S3204-08, with 18 mm × 18 mm detector area) for the detection. An NI USB-6009 interface card was used to digitize the analogue signal for subsequent transfer to a laptop computer using an USB cable. The other half of the light flux was fed to a compact spectrometer (Ocean Optics USB4000) with a 3 648 element silicon array detector of 29 mm width, covering the 400 – 900 nm spectral range. The entrance slit width was fixed at 200 μm, and correspondingly the spectral resolution was 5. 8 nm. The spectrometer was of the fiber-coupled type. A multi-core optical fiber was used at first to increase the light level. At a later stage, we placed the slit directly adjacent to the beam splitter so as to achieve enough sensitivity for monitoring weak night-time spectroscopic signals when using a metal-halide or tungsten lamp for illumination.

The probe volume of the system could be adjusted by a variable aperture size in the image plane, and was typically set to correspond to about 100 mm in diameter at the location of the dark box. The choice of aperture was made to achieve a high sensitivity for tiny insect species while suppressing residual background light. After carefully focusing the telescope on the dark-box plane, the intensity detector and the surface of the fiber leading the light to the spectrometer were both brought into the telescope image plane for high efficiency of light collection. It is worth noticing that putting a set of baffles in front of the main mirror as well as in front of the just mentioned aperture is quite helpful to reduce strong stray light at day-time. Telescopes are typically used for astronomy observations, and at night-time when the surroundings are in darkness, such baffles are no longer necessary.

During the diurnal observation, the FOV was illuminated by the natural sunlight. The midday transit time changed from 12. 25 to 12. 20 h Beijing time during the period of experiment (late August to mid-September, near autumn equinox) in Zhengzhou. The corresponding maximal sunlight angle of incidence decreased from 65 to 55 degrees during the study period. The sunlight angle of incidence with respect to the telescope FOV extended symmetrically to over 90 degree towards the sunrise and sunset directions. The smaller the illumination angle with regard to the line-of-sight, the more scattered light the detector received, because of the preferential forward scattering. Moreover, the sun-light intensity at the ground level is higher at noon because of a shorter distance through the absorbing and scattering atmosphere, as compared with the conditions in the morning and afternoon. The sunrise time and sunset time was around 6:00 am and 6:50 pm, respectively. In order to allow night-time observations we used a powerful lamp to illuminate the FOV from beneath as shown in Fig. 2(C).

The system was calibrated in two aspects, namely, geometrical (or intensity) calibration, and spectroscopic calibration. Both were achieved by bringing a small (around insect size), ambient-light-illuminated white polystyrene ball (with close to 100% reflectivity over all the spectral region of interest), suspended by a piece of thread, into the FOV. The recorded scattered intensity was strongly dependent on the position along the line-of-sight; thus each telescope distance had a specific geometrical calibration of the optical cross section. Likewise, the sun radiation changes throughout the day both in intensity and spectroscopic contents. The red curve in Fig. 3 shows a typical spectrum. This kind of calibration was referred to as temporal calibration and was performed once an hour typically at day-time. At night, when a stable artificial light source was used there was no need for periodical calibration. The calibration data were used as reference spectrum (S_r) to calculate the spectrally corrected reflectance spectrum (R) with $R = (S_s - S_b)/(S_r - S_b)$, where, S_s was the reflectance spectrum (spectrum of sample) of a flying insect recorded when it appeared in the telescope FOV, and S_b was the background spectrum recorded in the absence

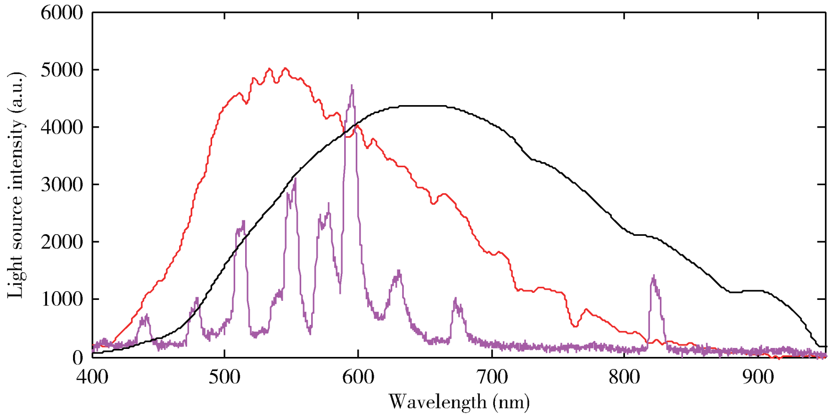

Fig. 3 Light sources with different spectral distributions

Day-time sun/sky radiation is shown as a red curve, with well-known Fraunhofer lines present. The 200 W tungsten lamp output is drawn in black. The metal halide lamp structured output is given in magenta.

of any insect. *R* is a dimensionless ratio, and the value is independent of the specific distribution of the light source. Influences of the spectral sensitivity of the detector are also eliminated. Thus, we can, *e. g.*, compare spectra of an insect studied at daytime and at nighttime.

2.3 Measurements and data analysis

The measurements were made either by releasing known insect species, where a measurement sequence of typically 10 - 20 s was initiated, or by intercepting naturally flying insects. The sampling rate was set to 3 000 Sa/s in order to allow a detailed temporal study, *e. g.*, of wing-beat frequencies after expansion of the temporal scale. In this case, the temporal wing-beat signal was Fourier transformed to obtain the corresponding frequency spectrum.

A detailed investigation of insect pests clearly benefits from spectroscopic characterization in addition to a wing-beat analysis. Spectroscopic information, also extending into the near-infrared region, beyond the cut-off at 700 nm of the human eye, was recorded simultaneously with intensity. Continuous spectral data were automatically stored in a folder with each file covering 100 ms records. Two groups of experimental data of released species were evaluated in the present study. The first experiment was for comparing spectra between two similar grasshoppers, *X. brachycerus* and *A. cinerea* during the day, and the second was for comparing *C. punctiferalis* spectra between day and night.

At night time the FOV was firstly illuminated with the metal halide lamp, used for attracting insects in the vertical looking light-trap. In a pre-trial experiment, a conventional 200 Watt tungsten lamp was placed 10 m away from the metal halide lamp to check which light source was more attractive to insects. It was indicated that the metal halide lamp constituted a powerful light source and was more attractive to insects than the Tungsten lamp, and thus was suitable for quantitative insect measurement. However, the strongly structured metal halide lamp output was clearly less suited for spectral measurement (Fig. 3). Further, this lamp showed an 80% modulation depth at 100 Hz, reflecting the 50 Hz AC of the electrical grid. This modulation makes wing-beat frequency assessment difficult even if Fourier transformation is applied to the data, because of the interference of the 50 Hz AC electrical frequency. We instead used a 200 Watt Tungsten lamp which had a broad-band spectrum. However, the electrical power source we employed had 30% intensity modulation at 100 Hz. The spectrum of this type of lamp peaks at about 650 nm instead of 530 nm for the sunlight case (Fig. 3). This is reasonable since the tungsten lamp represents a lower Planck radiation temperature. The reasonably well collimated light was directed to achieve as much overlap as possible with our FOV, especially in the area near the dark box. The sampling rate was set to 1 000 Sa/s at night-time when we aimed at recording spectroscopy rather than wing-beat frequencies.

In order to reduce the influence of moisture condensation near midnight, a plastic cover was put above selected parts of the system. Gentle electric heating could avoid moisture fall-out.

3 RESULTS

3.1 Continuous measurements of insect occurrence

The dark-field back-scattering detection system was tested with released insects and the tests indicated that the system could detect the released insects and record the insect occurrence continuously through day and night (Fig. 4). Considering that most pest insects, including *C. punctiferalis*, are nocturnal fliers, night-time recordings were highly desired. The system was then used as a trial to monitoring nocturnal insect pests continuously. In these measurements the metal halide lamp was placed on the ground, projecting a strong vertical light pillar into the night sky. The recording process covered more than 11 night hours, from 19:25 on 19 September to 6:23 on 20 September. We present here three 40-minute time span recordings in different stages of night-time (Fig. 5). The observation indicated that insects, large and small, were active shortly after dawn, and large species decreased dramatically near midnight. Small insects almost disappeared later in the night, leaving only few relatively large species flying before day break.

3.2 Wing-beat pattern

Successful releases of known insect species led to a signal burst of typically 50 - 200 ms duration depending on the type of flight track. Short-time duration was recorded when the insect was flying at right angle to the line-of-sight across the typical 100 mm of observation field, while long-time duration was recorded when the insect was flying along the FOV. Fig. 6(A) shows a typical long-time signal produced by a *C. punctiferalis* moth remaining a relatively long time in the FOV, therefore yielding more information on wing-beat characteristics. By Fourier transformation, the corresponding frequency spectrum of *C. punctiferalis* can be extracted. After subtraction of very low frequencies which were mainly contributed by the body of the insect, the fundamental

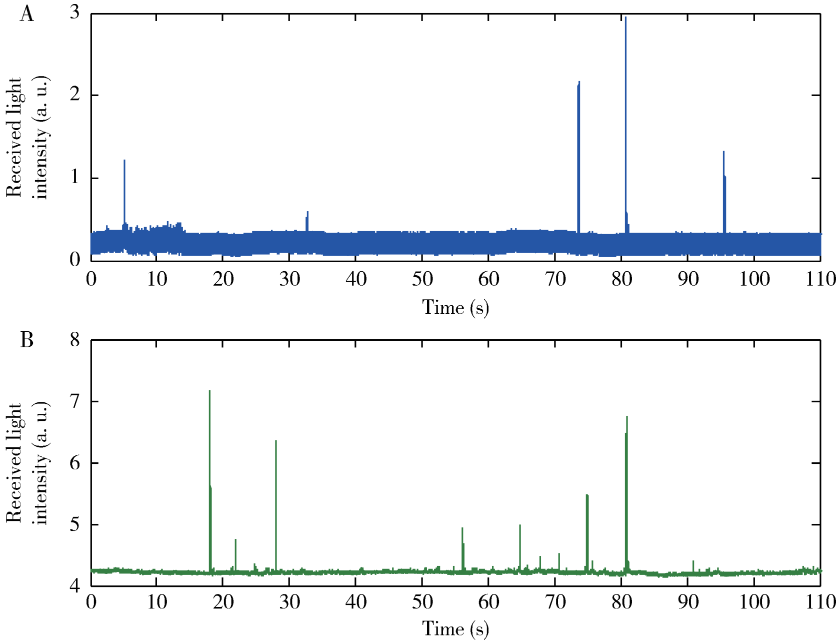

Fig. 4　Temporal recordings of insect hits

A: Nighttime recording at the 2nd experimental base of Henan Academy of Agricultural Sciences, where illumination by a metal halide lamp was employed. The two echoes first observed are from actively released insects, *Conogethes punctiferalis* and *Hymenia recurvalis*, respectively, while the remaining 3 echoes correspond to naturally occurring insects. The intensity modulation at 100 Hz of the baseline is due to the metal halide lamp employed at night; B: Daytime recording of naturally occurring insects at the experimental site in Henan Agricultural University. Insects producing echoes include dragonflies, damselflies and moths.

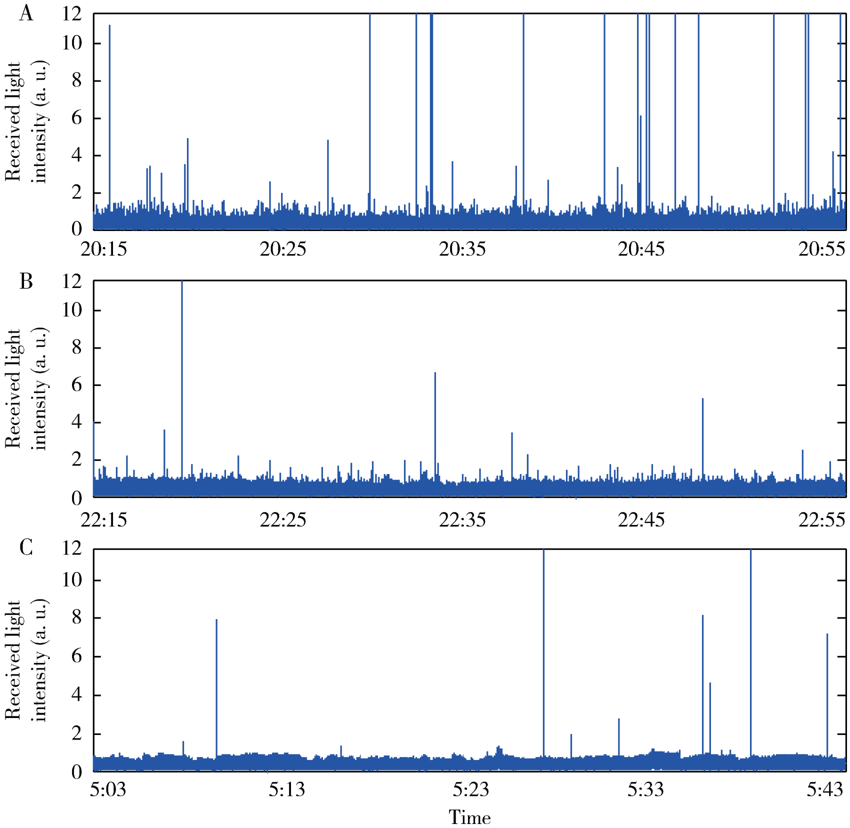

Fig. 5　Three selected 40-minute time span recordings

The recordings indicate nocturnal insect population density in early (A), middle (B) and late (C) stages of night-time.

frequency of 55 Hz, and the second and third overtones at 110 and 165 Hz, respectively, are clearly shown (Fig. 6: B).

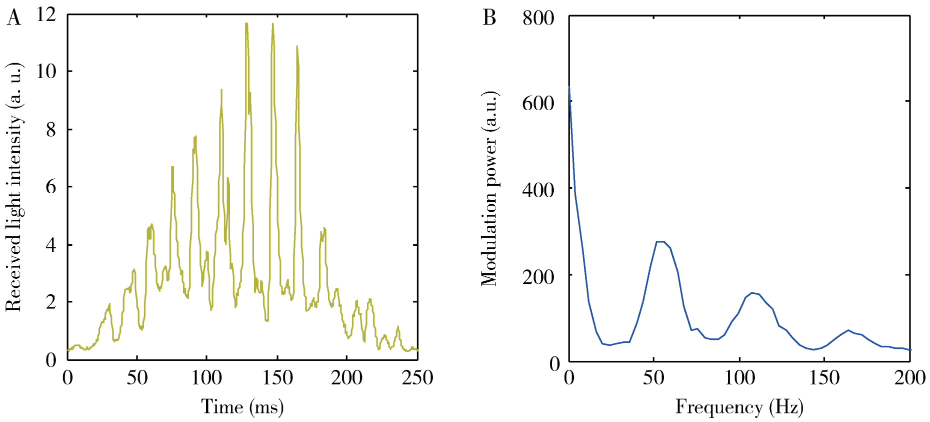

Fig. 6 Example of a recording of insect wing-beats

A: Recording of insect wing-beats from a released *Conogethes punctiferalis* moth; Tungsten lamp illumination was employed in night-time measurements. B: The corresponding Fourier transform.

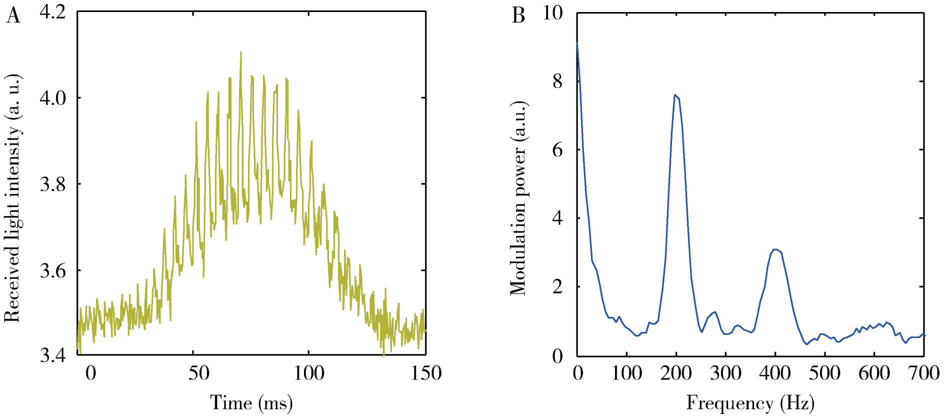

Fig. 7 Recording at day-time of 200 Hz wing-beats from a naturally flying insect of unknown species

A: The direct recording; B: The Fourier transform.

Fig. 7 provides a further example of insect wing-beat frequency assessment. It was produced by a diurnal insect flying into our probe volume and yielding a higher wing-beat frequency of 200 Hz than typical moths such as *C. punctiferalis* as described above.

3.3 Insect spectral signature

X. brachycerus and *A. cinerea* (Fig. 1) are diurnal species with strong hind legs, allowing jumping to rapid escape from natural enemies. After launch, they opened the wings flying in the air for several meters across the FOV of telescope and produced signature of reflectance spectra. As expected, the reflectance spectra were quite different between the two species (Fig. 8). The typical reflectance spectrum of *X. brachycerus* had low spectral contents in the visible region and was of low intensity which made it look dark as soil (protection color). Meanwhile it possessed fairly high intensity in the NIR region. The reflectance spectrum of *A. cinerea* peaked in intensity at around 580 nm. Clearly, it looks greenish to the eye.

A simple method to distinguish these two kinds of insects based on spectroscopy comes from forming a suitable contrast function. We here choose a simple ratio as such a function and define $R = I_{800\ \mathrm{nm}}/I_{560\ \mathrm{nm}}$ to tell the spectra of the two species apart. In this case, R of *A. cinerea* is clearly larger than 1.0, while that of *X. brachycerus* is clearly smaller than 1.0. More specific boundary values should result when more data are available. The same technique has been used in our previous work and worked out successfully.

Reflectance spectra recorded from two *C. punctiferalis* moths released at night-time presented quite similar curves (Fig. 9). Day-time spectra of this species were also measured by releasing two other individuals, and again spectra from these two individuals showed very similar appearance (Fig. 9). However, the night-time spectra exhibited relatively more red and near infrared radiation when compared with the daytime cases.

4 DISCUSSION

In the present study, we first demonstrated remote-sensing optical recordings of flying Chinese

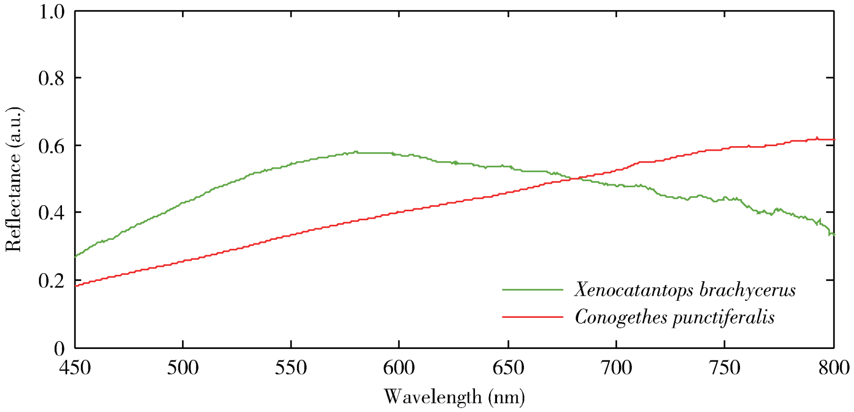

Fig. 8　Recording of day-time reflectance spectra of two released species of grasshopper

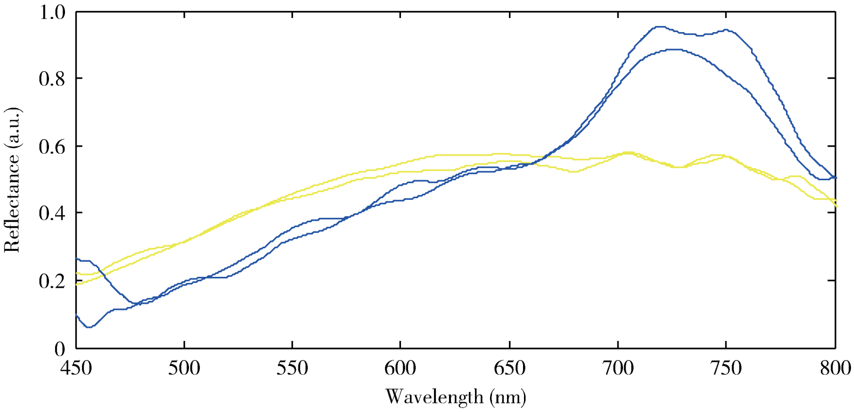

Fig. 9　Recording of day-time (marked with yellow) and night-time (marked with blue) reflectance spectra of released *Conogethes punctiferalis*

agricultural insects using a dark-field observation method, where light back-scattered from insects was observed against black background. Insect counts, wing-beat frequency analysis and reflectance (color) spectra recordings were all successfully achieved. This confirmed the possibility to monitor agricultural insect pests with a dark-field back-scattering detection system. Each released known insect species showed a unique reflectance spectrum character, which might help in remotely discriminating similar insect species which traditional radars cannot separate.

To observe nocturnal insects, we employed powerful artificial lamps to illuminate the FOV of the optical system, and this setup worked well at night time. However, the nocturnal insects might fly around the light source because of their phototatic trait. This may contaminate the counting results. Shifting the FOV far away from the illuminating light source might solve this problem. Using radiation with wavelengths to which nocturnal insects are insensitive for illuminating the FOV might be an even better solution. Both approaches need to be evaluated in the future.

The possibility of observing two or more insects simultaneously flying in the FOV is rather small given that in proximately 40 minutes we only got signals from hundreds of insects whose presence in the FOV is of the order of hundreds of millisecond. The introduction of a laser for FOV illumination would undoubtedly ensure a high contrast between our signal and the background; however, we would loose the information from the spectral domain in the meanwhile. The night-time reflectance spectral curve of *C. punctiferalis* was so different from those shown for the daytime case. In examining the wings of *C. punctiferalis*, it was notable that the color was quite different when viewed from the dorsal versus the ventral side of their wings. The dorsal side is typically bright yellow scattered with black spots (Fig. 1), while the ventral side is dark yellow with clear black stripes. This difference also became clear in laboratory spectroscopic reflectance measurements (Li *et al*., 2016). The sunlight mostly shone on the dorsal surface of the wings from above (Fig. 2: B), while the tungsten lamp mostly shone on the ventral surface of the wings from below at night-time (Fig. 2: C). This explains the difference in reflectance spectrum of the same species between day-time and night-time, but posed an important question, *i. e.*, how to set up the system to produce stable insect signatures in reflectance measurements? The design of vertically looking radar may be used as a reference, where the insects uniformly show the ventral side to the radar (Chapman *et al*., 2003).

Runemark *et al*. (2012) demonstrated the ability of a simple remote dark field spectroscopy system in discriminating between sexes of two damselfly species. We measured the reflectance spectra of three common species of agricultural insect pests in the present study and seven other species in our parallel study (Li *et al*., 2016). These data showed unique characters in the reflectance spectrum for each species that might be used to discriminate between species. However, as compared with about 200 common insect species trapped in farm lands of northern China, the measured species only account for a small portion of the nocturnal insects. Moreover, the measured data were collected from only one or two individuals for each species and the variation in spectral characters within species was not clear. Old moths or long-distance migrants may loose some scales. Whether this changes the spectral character is unknown and is worth further study.

ACKNOWLEDGEMENTS The authors gratefully acknowledge the support of Prof. HE Sai-Ling from South China Normal University and Zhejiang University, and Prof. Katarina SVANBERG from South China Normal University and Lund University.

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利用基于光学暗场反射测量的光学遥感技术探测飞行的农业害虫

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摘要：【目的】本研究的目的是开发一种光学遥感技术实现在农田昼夜连续自动地监测农业害虫。【方法】一个望远镜通过对准远处的暗箱，得到一个低亮度水平的基线。当昆虫在望远镜的视野中飞过时，它散射的太阳光的光学信息就被连接到望远镜的记录系统采集到。在夜晚我们使用很强的灯光替代太阳光来照亮昆虫。【结果】昆虫计数、昆虫的振翅频率分析及反射光谱记录都获得成功。这表明使用暗场背向散射探测系统监测昆虫是可行的。手动释放的已知昆虫种类都具有独特的光谱特性。几种害虫特别是桃蛀螟 *Conogethes punctiferalis*（Guenée）和短角异斑腿蝗 *Xenocatantops brachycerus*（Willemse）都用本文描述的方法进行了成功识别。【结论】用暗场背向散射探测系统昼夜连续监测田间农业害虫是可行的。跟预期的一样，散射的振翅频率和光谱信息可以用来识别害虫。

关键词：光学遥感；暗场背向散射探测；昆虫；桃蛀螟；短角异斑腿蝗

中图分类号：Q968　　**文献标识码：**A　　**文章编号：**0454-6296(2016)12-1376-10

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